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PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c).

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EV 216213233 US

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<input type="checkbox"/> Additional inventors are being named on the _____ separately numbered sheets attached hereto					
TITLE OF THE INVENTION (500 characters max)					
SIMULTANEOUS PHASE SHIFTING MODULE FOR USE IN INTERFEROMETRY USING SINGLE AND MULTIPLE LIGHT WAVELENGTHS					
Direct all correspondence to:		CORRESPONDENCE ADDRESS			
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ENCLOSED APPLICATION PARTS (check all that apply)					
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Respectfully submitted,

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Date 03/31/2003

REGISTRATION NO.
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USE ONLY FOR FILING A PROVISIONAL APPLICATION FOR PATENT

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CASE DOCKET NO.: 6166.003

APPLICANT(S): PIOTR SZWAYKOWSKI, RAYMOND CASTONGUAY and FRED BUSHROE

APPLICATION TITLE: "SIMULTANEOUS PHASE SHIFTING MODULE FOR USE IN INTERFEROMETRY USING SINGLE AND MULTIPLE LIGHT WAVELENGTHS"

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Kathleen C. Tennant

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- ☐ Utility Patent Application Transmittal sheet
- ☐ Fee Transmittal sheet (in duplicate)
- ☐ Declaration for Utility or Design Patent Application
- ☒ A description of the invention.
- ☐ Power of Attorney or Authorization of Agent
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- ☐ Assignment Agreement and Recordation Cover Sheet
- ☐ Nonpublication Request Under 35 U.S.C. 122(b)(2)(B)(i)
- ☒ One sheet of drawings.
- ☐ photographs submitted as informal drawings for reference purposes only.
- ☐ Information Disclosure Statement
- ☐ Copies of prior art
- ☐ Copy of priority document

PROVISIONAL PATENT APPLICATION

TITLE OF INVENTION: "SIMULTANEOUS PHASE SHIFTING MODULE FOR USE IN INTERFEROMETRY USING SINGLE AND MULTIPLE LIGHT WAVELENGTHS"

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SIMULTANEOUS PHASE SHIFTING MODULE FOR USE IN INTERFEROMETRY USING SINGLE AND MULTIPLE LIGHT WAVELENGTHS

Field of the Invention & Introduction

The present invention relates to interferometry, in particular, interferometry involving the measuring of wavefronts through use of phase-shifted interferograms. Specifically, the present invention relates to interferometers with reduced sensitivity to vibration for use in capturing data from stationary objects and moving objects.

Description of Related Art

Interferometers have been around for a long time. Interferometry is a widely used method for measuring surface profiles (often to nano-meter resolutions) and other physical properties of materials, gases and liquids. There are many types of interferometers, characterized by their optical designs and layouts. Some classical types are Twyman-Green, Fizeau, Michelson, Mach-Zender, and Fabry-Perot. Each of these interferometer types produce interference patterns, called interferograms. These interferograms can be used to analyze characteristics of an object under test (see, FIGURE 4).

Interferograms are generated by the interference of a test wavefront and a reference wavefront. The test and reference wavefronts originate from a common "source" wavefront; they are obtained by splitting the source wavefront. The test wavefront then obtains its "test" information, by interacting with the object under test (typically by reflecting off of, or transmitting through a test object). Similarly, the reference wavefront obtains its "reference" information, by interacting with a "known" reference object, such as a super polished flat glass plate. Superimposing these two wavefronts spatially (i.e. on a flat screen, or on an image sensor such as a CCD) produces an interferogram.

Interferometers require coherent superposition of a "test beam" (of light) with a "reference beam" resulting in the formation of an interferogram in the overlapping region of the two beams. This interferogram data can then be captured using various types of detectors, such as a camera, for analysis.

The spatial distribution of intensity levels within the interference pattern (see Figure 4) relates to differences in the phase of the test and reference wavefronts. Note that the reference wavefront is acted on by a known "measurement standard", such as an optical "reference" surface, and the test wavefront is acted on by the unknown object under test. Measuring the difference between the two wavefronts allows the test wavefront to be determined. In other words, the process is akin to comparing the "unknown" test wavefront to a "known" standard, the reference wavefront.

A single interferogram is usually insufficient to obtain the accuracy required for most applications. A variety of methods have been developed to acquire multiple phase-shifted interferograms as a means to increase accuracy and resolution of the measurement. Phase-shifting techniques require altering the phase between the two interfering wavefronts by introducing controlled phase delays between the test and reference beams. These added phase-shifts supply additional information that can be used to compute the test wavefront significantly more accurately. Almost all techniques of phase shifting use sequential or "temporal" methods to introduce phase differences while multiple interferograms are acquired serially in time. However, in practice, these temporal methods cannot be used in the presence of relatively fast changing environmental conditions (such as vibrations, air turbulences, etc), or, when the object under test cannot be stabilized (i.e. vibrating), or when the object under test is in motion. For example, problems can arise because the interferometer takes 3 to 12 frames, (pictures) or phase shifted interferograms, serially in time, (typically spaced 30ms apart for standard video), and during this acquisition time (for 3 to 12 frames), any vibration that occurs between the test and reference object causes inaccuracy and undesired results.

Thus, methods have been developed to acquire multiple phase-shifted interferograms simultaneously. These methods usually require that the reference and test beams ("beams" and "wavefronts" used interchangeably herein, with a "wavefront" being understood as propagating along the optical axis and sweeping out a volume that defines the light beam) be orthogonally polarized, thus allowing independent access to either one of these beams (such as via polarization optics), even when they are spatially overlapped. With this "independent access", multiple phase-shifts can be introduced simultaneously (as opposed to temporally), by retarding or advancing the phase of one beam with respect to the other. Altering the phase of a beam is typically accomplished through the use of wave plates or polarization beam splitters. In practice,

this is accomplished by splitting the superimposed test and reference beams into three or more channels with each new channel having orthogonally polarized test and reference beam components. For each new channel, one of the beam components (test or reference) is then phase-shifted relative to the other beam component. This phase shift, or phase delay, is adjusted to be different in each channel. There are multiple methods for splitting the superimposed test and reference beams into multiple channels and multiple methods for phase-shifting within each channel.

A method proposed by J.W. Schwider (German Patent No. DE 196,52,113,A1) uses a diffractive optical element to split a beam composed of mutually orthogonally polarized test and reference beams into three (or more) channels. Schwider uses a set of quarter wave plates followed by a common polarizer to introduce desired phase-shifts. The quarter wave plates are placed in two of the three beams. One wave plate is orientated with its fast axis along the polarization direction of the test beam, while the other is oriented along the polarization direction of the reference beam. The phase delays introduced by the quarter wave plates are thus $-\pi/2$ and $\pi/2$ respectively (and the phase differences between the three beams are $-\pi/2$, 0 , $\pi/2$). Although diffractive elements appear attractive as beam splitters, actual diffractive components are difficult and expensive to produce. This approach also assumes that the three resulting beams are imaged onto a single detector array such as a CCD camera. Thus expensive non-standard cameras preferably must be used to achieve high spatial resolution. Also, it can be difficult to ensure that each of the wavefront images is positioned to within sub-pixel accuracy, which is required for accurate analysis. Alignment cannot be accomplished simply by positioning the camera itself, as that would change the position of all interferograms simultaneously with respect to the detector's pixels. Thus interferogram image placement preferably must be done using optical components. Also, this method makes use of three diffraction orders that, in general, have different intensities (due to different diffraction efficiencies for the 0-th and ± 1 diffraction orders), which results in inconsistencies with the general requirements of the phase-shifting method. A similar approach has been offered by Millerd, U.S. Pat. No. 6,304,330.

Another approach to simultaneous phase shifting uses a combination of beam splitters and polarization beam splitters to split the beam into four wavefronts. The desired phase shifts are obtained through a combination of quarter wave plates and proper orientation of polarization

beam splitters with respect to polarization directions of the incoming test and reference beams. See Chris L. Koliopoulos, "Simultaneous phase shift interferometer", Proc. SPIE Vol. 1531, p. 119 (1992). The phase delays obtained from this configuration for the four output beams are fixed and equal to 0 , $\pi/2$, π and $3\pi/2$ (0 , 90° , 180° and 270°). These implementations project the interferogram onto four standalone CCD cameras. One challenge with using multiple standalone cameras is the need to maintain position of these cameras to within sub-pixel accuracy, with the relatively complex geometry of this system. Although previous attempts in positioning these cameras have been successful, maintaining their positions has been problematic in real world environments. This is due to the realized complex geometry and spatial separations of the cameras. Another requirement for multiple cameras is ensuring that all camera signals are synced together so that the camera images are acquired simultaneously. Previous methods performed this task utilizing expensive and complex schemes, such as genlocking the cameras with a common sync signal – then using either multiple frame grabbers or an expensive computer board with multiple independent frame grabbers on the same board, to acquire the video signal from each camera. Another significant problem with the aforementioned methods is physical size. Because of their design, they are large and bulky.

Thus, there is a desire for an improved interferometer, or a module adapted for use with an interferometer, which renders the interferometer less sensitive to vibrations so as to increase and improve performance capabilities. The desire includes greater and better performance capabilities in capturing data from stationary objects and from moving objects.

Summary of the Invention

The present invention is directed to an apparatus, for use as a back-end of an optical interferometer, and related method, that measures wavefronts by simultaneously producing a set of phase-shifted interferograms. In one embodiment, the apparatus can be used as a "phase shifting module" in a variety of different interferometers whose front-end is capable of producing test and reference wavefronts which are orthogonally polarized with respect to each other. (It is understood by one of ordinary skill in the art that the phrase "orthogonally polarized," as used herein, includes not only linear polarizations that are perpendicular such as "s" and "p" polarizations, but any state of orthogonal polarizations, such that the vector product

equals zero, for example, right-hand and left-hand circular polarizations.) In particular, the phase shifting module of the present invention receives the orthogonally polarized test and reference wavefronts and simultaneously divides them to produce three or more phase-shifted interferograms. The resulting simultaneous acquisition of multiple interferograms by the module advantageously enables relatively very fast simultaneous data collection. As such, the module of the present invention, as part of or used with an interferometer, enables (i) measurements of relatively fast moving objects, and (ii) measurements in the presence of vibration, over conventional interferometers.

In particular, the present invention uses a compact assembly of optics and CCD cameras for measuring test object parameters by producing three or more simultaneously phase-shifted interferograms. The assembly is composed of optics and CCD arrays that can be bonded together to form a single monolithic module. This enables the phase shifting assembly to be miniaturized and robust, not prone to misalignment in rugged and harsh environments. Since multiple interferograms are acquired simultaneously, fast camera frame rates and shutter speeds can be used to capture interferograms of dynamic events. The ability to capture phase shifted interferograms simultaneously also eliminates the need for expensive vibration isolation, and enables an interferometer to be use in dynamic environments; this enables the use of interferometry in portable and hand held instruments.

The present invention can be used to measure material properties such as gas density, index of refraction, three dimensional surface profiles, and dynamic properties of fast moving objects such as dynamic MEMS (Micro Electro-Mechanical Systems).

Brief Description of the Drawings

Figure 1 is a plan view of an embodiment of the present invention;

Figure 2 is a plan view of another embodiment of the present invention; and

Figure 3 is a plan view of yet another embodiment of the present invention.

Figure 4 is an example interferogram.

Description of the Invention

Figure 1 illustrates an embodiment of the present invention, with individual items separated for clarity and ease of reference. Coming from the front-end of an interferometer, beams 7, composed of superimposed test beam 7t and reference beam 7r, enter a cube beamsplitting assembly 5 at position 8, whose diagonal "splitting" surfaces are 50% reflective and 50% transmissive, and which, in this described embodiment, is not a polarizing beamsplitter. The superimposed beams 7 travel through the cube beamsplitter assembly 5 and are initially split at a first beamsplitting surface 5a. The split ratio of this surface is preferably 50:50, and is preferably the same for the S and P polarization. It bears notice, that after the initial split, both beams 71 and 72 preserve all properties of the incoming beam 7, except intensity. In the preferred embodiment an x-cube beam splitter is used to split the beam four ways with each beam having equal path length and passing through the same number and type of optical elements.

In the next step, the two beams 71 and 72 travel through areas of other beamsplitting surfaces 5b and 5c with the identical optical properties as surface 5a. As a result, four beams 711, 712, 721 and 722 are formed as outputs of the beamsplitting assembly 5. These four output beams have the same properties of the incoming beam 7, except for its intensity being at one-fourth of the initial intensity. In the described embodiment, the present invention is advantageously configured so that each channel travelled has identical optical paths, composed of identical optical components. This symmetry is valuable in minimizing nonsymmetrical aberrations (both optical and polarization) between each of the channels. These identical channels substantially eliminate the need to re-space elements with air gaps, or insert blank optics, to achieve equal path lengths (and magnification). This substantially simplifies the manufacturability of a monolithic form of the present invention.

From the description of the beam splitting assembly 5, it is understood by one of ordinary skill in the art that the number of beam splitting surfaces, encountered by any one output beam, is not limited to those described above, but is (at least theoretically) unlimited. In order to fulfill requirements to use common phase-shifting algorithms, at least three output beams are generally necessary to generate three phase shifted interferograms. If more beams are used and more interferograms generated, certain errors are eliminated or minimized, and measurement accuracy

can be greater. In the described embodiment, three output beams are used to calculate phase of the test beam. In this case, output beams 712, 721 and 722 enter quarter-wave plates 3a, 3b, and 3c, respectively, where the polarization of the wavefronts corresponding to both test and reference beams are converted to circular polarizations.

The wavefronts 712, 721 and 722 then enter polarizers, 2a, 2b, and 2c, respectively. The polarizers define a common polarization state for each pair of test and reference beams, enabling formation of interference fringes. Each interference pattern behind the polarizer is phase-shifted by an arbitrary but known value, depending on the angular rotation of each polarizer's axis. This rotation orientation can be controlled with relatively high accuracy. This rotation defines the phase delay between the test and reference beams. For example, phase delay values such as $\pi/2$ or $\pi/3$ can easily be produced, or in fact, any other value that may be required by a phase recovery algorithm. For a given channel, or output beam, the phase shift can be introduced or changed by simply rotating the polarizer. The phase-shifted beams then enter cameras 1a, 1b, and 1c where they form interferograms on image sensors, and are converted to electrical signals 4a, 4b, and 4c. The signals then travel to a frame grabber 6 for conversion into images and then into a computer 9 for analysis. In the preferred embodiment progressive scan cameras are used.

The described embodiment advantageously uses a single inexpensive color (RGB) frame grabber for conversion of signals 4a, 4b, and 4c, where RGB represents the red, green, and blue channels of a color frame grabber. A common, inexpensive, RGB frame grabber has three channels, so this can be used to capture the three output images simultaneously. Using a three channel RGB frame grabber has other advantages such as displaying all three camera channels 1a, 1b, and 1c overlaid on a video monitor as a single color image in real time, or as three separate images in real time. Also this method allows real-time subtraction of one image with respect to another. Both of these features allow real-time verification of sub-pixel alignment for all three cameras, and can be used for various test object analyses techniques. Unique to this invention is the flipping of one or two of the images on cameras 1a, 1b, or 1c either electronically or computationally using software. Electronic flipping can be a simple dipswitch setting on a camera, using image processor 6, or through the use of a separate electronic circuit. Flipping some of the images are required since some of the images on cameras 1a, 1b, and 1c can be mirror images of each other due to the number of different surface reflections in two of the beam

paths. In typical situations such as this, a mirror reflection would normally be introduced to flip the desired images resulting in all images being oriented in the same direction relative to cameras 1a, 1b, and 1c. Flipping electronically or through software eliminates these extra mirrors which is a significant advantage in keeping the entire optical assembly small and compact. Another major advantage is that frame grabber 6 and computer 9 can be replaced by an RGB video to DVD disk, VCR tape recorder, or digital memory. This allows signals 4a, 4b, and 4c to be recorded in real-time and then processed at a later date. Extremely fast events in harsh environments can be monitored in this fashion. This also decouples the computer from the interferometer, which allows data to be captured very quickly and passed over a network or transmitted wirelessly to be processed offsite. The method of recording simultaneous phase-shifted data or transmitting simultaneous phase-shifted wirelessly or through a network - independent of a computer can be applied to any simultaneous phase-shifting method.

Referring to Figure 2, another embodiment of the present invention involves a monolithic assembly 10 of items 1, 2, 3, and 5, which is presently the best mode of the invention. This, as understood by one of ordinary skill in the art, can be accomplished through a combination of adhesives, or laser welding parts together, or fixing parts on a common base in close proximity. The resulting monolithic unit, if cemented together, has no air-gaps between optical surfaces, has common beam path with common optical elements, and can resist misalignment and damage in rugged and harsh environments. Also, the monolithic unit can be miniaturized allowing it to be used in handheld instruments for indoor and outdoor applications. This configuration of the instant phase shifting module advantageously integrates beamsplitters, waveplates, polarizers, and cameras resulting in a complete phase-measuring module that can be one cubic inch in size or smaller.

Referring back to Figure 1, a fourth wavefront pair 711r and 711t exits the beamsplitting assembly 5. A fourth camera (not shown) can be used to acquire this fourth interferogram. This fourth channel can also be used for an imaging system for viewing the test sample or other means of optical inspection.

Figure 3 illustrates a configuration using two modules 10 together to generate six or eight phase-shifted interferograms. This allows more sophisticated algorithms to be used that could enhance accuracy or compensate for other types of errors, such as camera non-linearities. The parallel architecture can be continued indefinitely for any number of phase-shifted. Referring to

Figure 2, the source beam 7 can be pulsed in sync with camera 1a, 1b, 1c for measurement of fast events. The source beam 7 can be a laser, LED, VSCSEL, or other sources.

Unique to the invention, the parallel architecture of Figure 3 also allows a second beam 11 composed of orthogonally polarized wavefronts but having a different wavelength than that of beam 7. This allows much greater dynamic height ranges of measurement over small spatial frequencies to be made due to the different wavelengths using interferometric algorithms. This is due to the modulo 2PI limitation when using single a wavelength. Beams 7 and 11 pass through beam splitter 13 and also reflect off of surface 13a. Optical band-pass filters 12a and 12b allow only a narrow band of light to pass through. Thus 12a can be selected or tuned to pass beam 7 only, while 12b is selected or tuned to pass beam 11 only. Two sets of modules 10 then perform the same function on both beams for phase-shifted interferogram acquisition resulting in two sets of phase-shifted interferograms. This is a significant advantage over prior art, since in this invention, all phase-shifted interferograms, at different wavelengths, are acquired simultaneously. Again the parallel architecture can be continued indefinitely for acquiring any number of phase-shifted interferogram sets, with each set at a different wavelength. Optical filters 12a and 12b can be fixed filters, variable mechanical filters, tunable grating filters, liquid crystal tunable filters, or other filter types. Using tunable filters allow the selection of height dynamic range and resolution of the measurement. Referring to Figure 2, the source beams 7 and 11 can be pulsed rapidly in sync with cameras 1a, 1b, 1c for measurement of fast events. The source of beams 7 and 11 can be a laser or lasers, a LED or LEDs, VSCSEL, or other sources. Beams 7 and 11 can have a common source with a larger wavelength bandwidth. This allows filters 12a and 12b to select smaller bands of light within the single common source. In the preferred embodiment components 10 (two of them) and 13 can be combined into a single monolithic module for multi-wavelength simultaneously phase-shifted interferogram acquisition in rugged environments. This module can be two cubic inches in size or smaller.

Another embodiment for multi-wavelength measurements uses a three wavelengths, preferably red, green, and blue (RGB). This method is used for a variety of applications including for the measurement of fast step height changes on surfaces. This method has been described in detail by Johannes Schwider in Applied Optics, February 2003, Vol 42 No 4, page 667. The Schwider RGB method uses separate red, green, and blue lasers and a PZT for phase shifting. In the proposed invention, the source beam 7 can be a combination of red, green, and

blue beams. Each of these three beams are composed of orthogonally polarized test and reference wavefronts. All three beams would then pass through beam splitting assembly 5, then through quarter wave plates 3a,3b,3c and then through polarizers 2a,2b,2c. The beams would then project onto cameras 1a,1b,1c. In this RGB mode, optical components 3a,3b,3c and 2a,2b,2c would be selected to perform across the RGB wavelength range and cameras 1a,1b,1c would be color cameras. The color cameras can be 3CCD color cameras, 1 CCD color cameras, or in the preferred embodiment they can be a color camera using Foveon technology, which has the advantage of the RGB color pixels being layered in the z-direction as compared to in the x-y plane of the CCD. The real time collection of three phase-shifted wavelengths has significant advantages in speed and robustness. In a preferred embodiment the three lasers can be replaced by a single white light source such as a white light laser or white light LED.

It is understood by one of ordinary skill in the art that the described embodiment of the invention can be modified such that one of the quarter wave plates (for example 3c) in front of a camera could be removed, and the path length to this camera made equal to the others by re-spacing the camera or adding a blank makeup glass. Moreover, the described embodiment of the invention can also be modified by using a diffraction grating instead of the beamsplitter 5, and using only one CCD (or multiple CCD's), where a quarter waveplate and rotatable polarizer are positioned in front of each of the split channels, before the image sensor.

Further, the three quarter wave plates (3a, 3b, and 3c) can be replaced by one-quarter waveplate in front of the beamsplitter 5, providing that the beamsplitter 5, at each output beam, preserves the circular polarization of the input beam. Similarly, a quarter waveplate can be placed in front of a diffractive type beamsplitter (as such beamsplitter can be made to preserve the circular polarization of the incoming beam), where a quarter waveplate and rotatable polarizer are positioned in front of each of the split channels (before the image sensor).

Also, the three quarter waveplates (3a, 3b, and 3c) can be removed and one quarter waveplate placed in front of the beamsplitter 5. Where the beamsplitter 5 does not preserve the circular polarization of the input beam, a waveplate of necessary retardation can be used in front of the polarizers (2a, 2b, and 2c) to compensate for the phase delay introduced by the beamsplitter. The beamsplitter 5, can be any beamsplitter with equal intensity outputs and equal path lengths. For example, prism arrangements such as X-Cube, K-prism, Phillips Prism

extended to more than three cameras, or others, and extensions of the prism arrangements to make an even greater number of outputs. This method of dual/multiple wavelength simultaneous capture can be used with other methods of simultaneous phase-shifting interferometry.

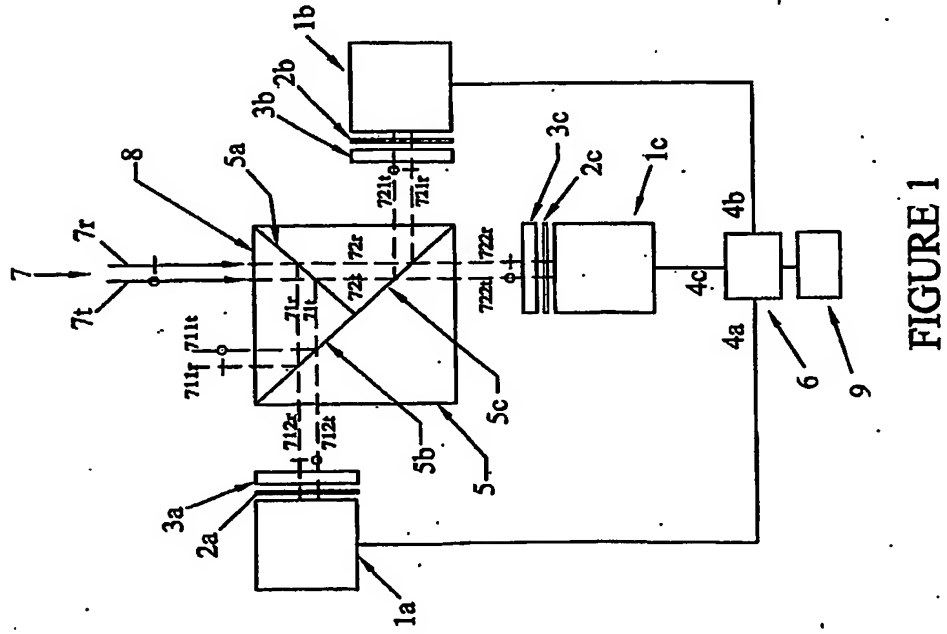
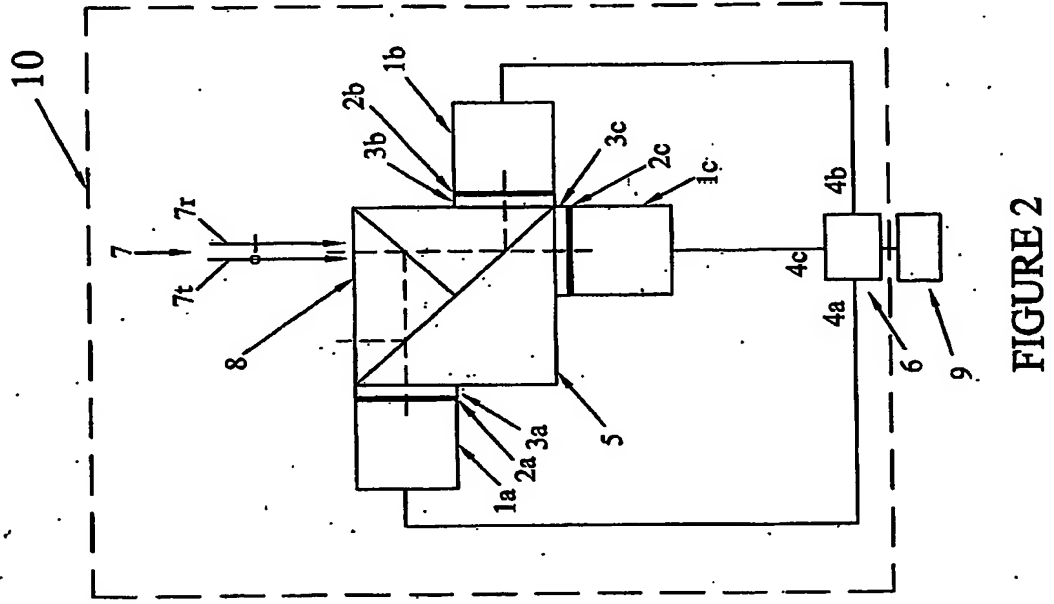
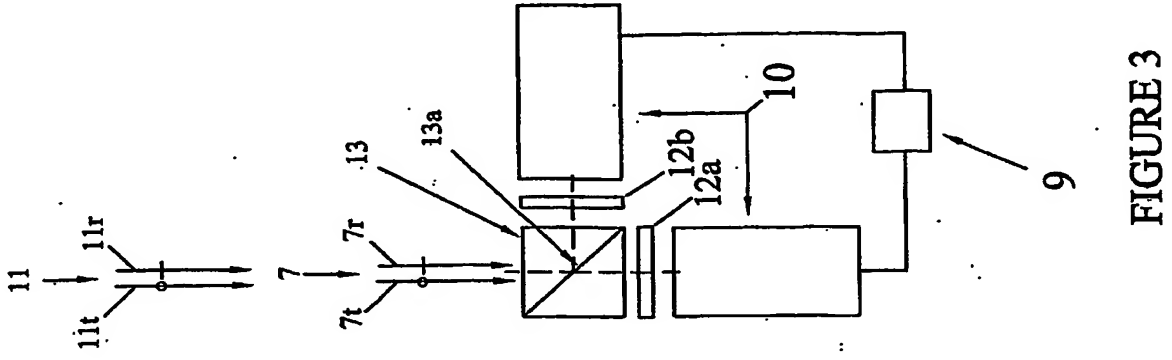
Other modes of unique operation.

Single chip cameras can also be used and monolithically adhered to the beamsplitting assembly.

Use of a gradient tunable filter.

Simultaneous phase-shifting handheld unit.

Simultaneous phase-shifting fiber inspection unit.



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